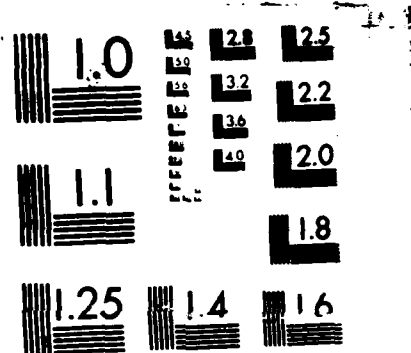AD-A179 751   CHANNELING-RADIATION MEASUREMENTS AT LAWRENCE LIVERMORE   1/1
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In the past few years, the amount and quality of channeling-radiation data have increased enormously, owing largely to much improved experimental capabilities. Current results include improved interplanar potentials for diamond, the description of the effect of platelets in diamond as an average thermal vibration, an improved determination of the Debye temperature of silicon, an improved determination of the thermal-vibration amplitude of LiD, and the demonstration that LiF crystal structures can survive intense electron bombardment.

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CHANNELING-RADIATION MEASUREMENTS AT LAWRENCE LIVERMORE NATIONAL LABORATORY

B.L. BERMAN * and B.A. DAHLING

Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550, USA

S. DATZ

Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

J.O. KEPHART, R.K. KLEIN, R.H. PANTELL and H. PARK

Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA

In the last few years, the amount and quality of channeling-radiation data have increased enormously, owing largely to much improved experimental capabilities. Current results include improved interplanar potentials for diamond, the description of the effect of platelets in diamond as an average thermal vibration, an improved determination of the Debye temperature of silicon, an improved determination of the thermal-vibration amplitude of LiD, and the demonstration that LiF crystal structures can survive intense electron bombardment.

1. Introduction

At the 6th Conference on the Application of Accelerators in Research and Industry in 1980 we reported [1] the discovery of channeling radiation at Lawrence Livermore National Laboratory (LLNL) [2–4], the measurement of some of its properties [2,4,5], our early attempts to fit the data with phenomenological theories [6,7] (see also refs. [8–10]), and some prognostications as to its future applicability (see also refs. [11–13]).

Since that time, we have greatly improved our experimental capabilities, and we have extended our channeling-radiation studies considerably, both with positrons and electrons from the LLNL Electron–Positron Linear Accelerator, on a variety of crystal species. These include, in addition to silicon, LiF [14–16], germanium [17], and diamond, both with and without platelets [18–22] (see also ref. [23]). Most recently, we have studied channeling radiation from LiH and LiD [24], BeO [25], tungsten [26], and GaAs [27].

A recent description of our experimental apparatus and procedures can be found in ref. [21]. Our theoretical analysis now is based upon the quantum-mechanical many-beam formalism (also see ref. [21]), first utilized in this field by Anderson et al. [28,29]. Examples of a number of current topics are described briefly in this

* Present address: Department of Physics, George Washington University, DC 20052, USA.

paper. A more extensive review of channeling-radiation experiments performed both at LLNL and elsewhere will appear shortly [30].

2. Diamond

Perhaps the best crystal with which to study channeling radiation is diamond, because of its high Debye temperature and its low Z. These are desirable because the primary limitation on the coherence length for electron channeling results from the atomic thermal vibrations, and the cross section for this scattering process varies as $\sim Z^2$ and increases with vibrational amplitude, which decreases as the Debye temperature increases. A large coherence length in turn implies narrow spectral line structure. Indeed, the first measurement of channeling radiation from diamond [31] showed remarkably sharp structure.

Our recent results for the (110) channeling-radiation spectra at three incident electron-beam energies are shown in fig. 1, together with the many-beam calculation of transition energies and strengths from the "standard" Hartree–Fock potential (see ref. [21] for details). It can be seen that there is reasonable agreement between experiment and theory, although there is a slight tendency for the calculated transition energies to lie higher than the experimental spectral peaks. For the (111) plane, however this tendency is much exag-
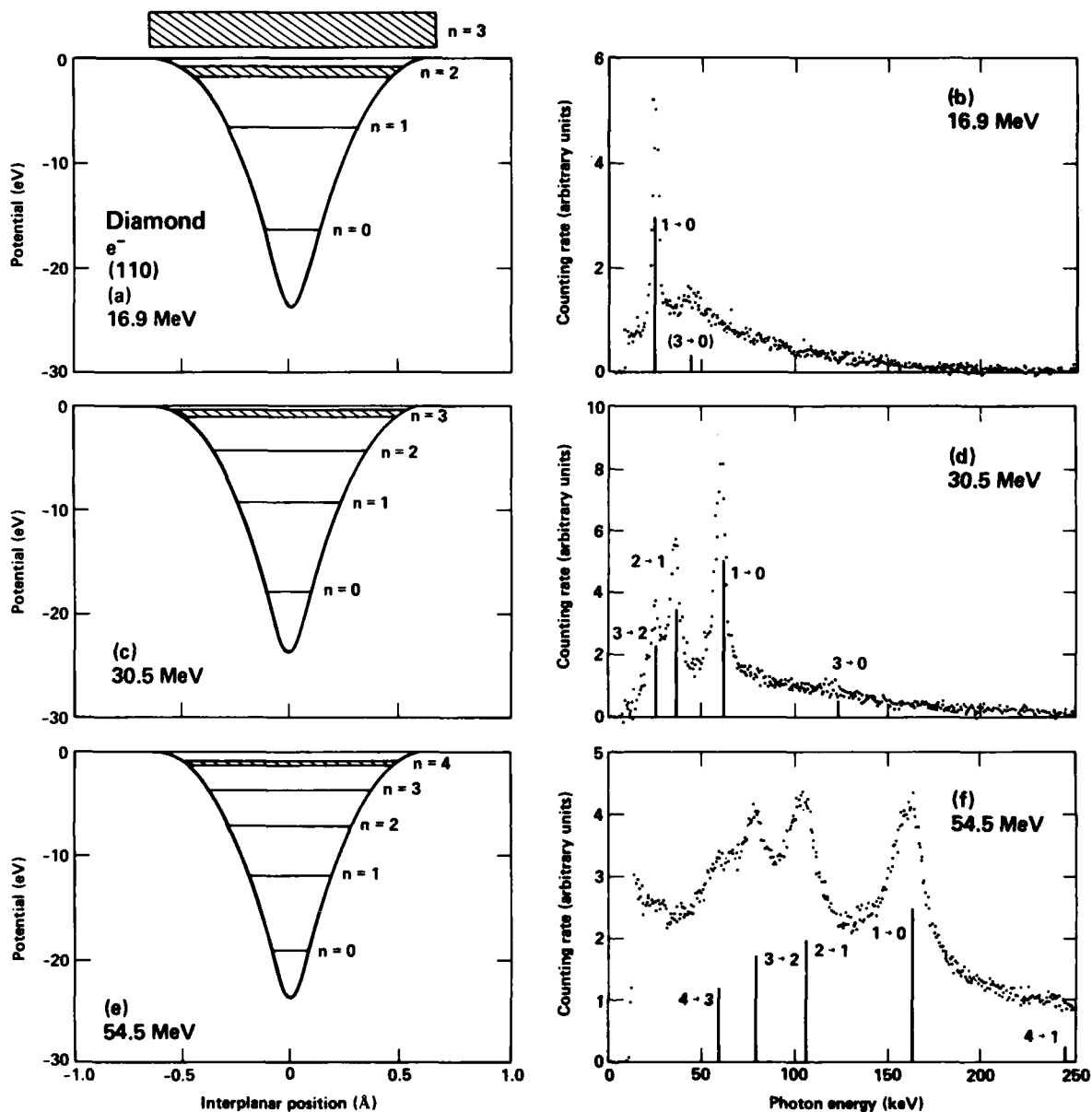
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Fig. 1. The (110) potential and eigenvalues [parts (a), (c), and (e)] and channeling-radiation spectra [parts (b), (d), and (f)] for 16.9-MeV, 30.5-MeV, and 54.5-MeV electrons, respectively, channeled in diamond. Note the increase with electron-beam energy of the line energies and linewidths.

gerated, as shown in fig. 2. Because a (111) potential obtained from X-ray diffraction data and especially an empirical potential fitted to the data both are shallower than the standard potential and both fit the data better, we believe that the fact that significant charge in the diamond crystal is distributed along the ⟨111⟩ valence-bonding direction alters the (111) interplanar potential as shown in the figure, and in fact these data serve as a

quantitative measure of this asymmetric charge distribution [21].

3. Platelets

Platelets in diamond [nitrogen mono- or di-layers precipitated along the (100) planes] influence the chan-
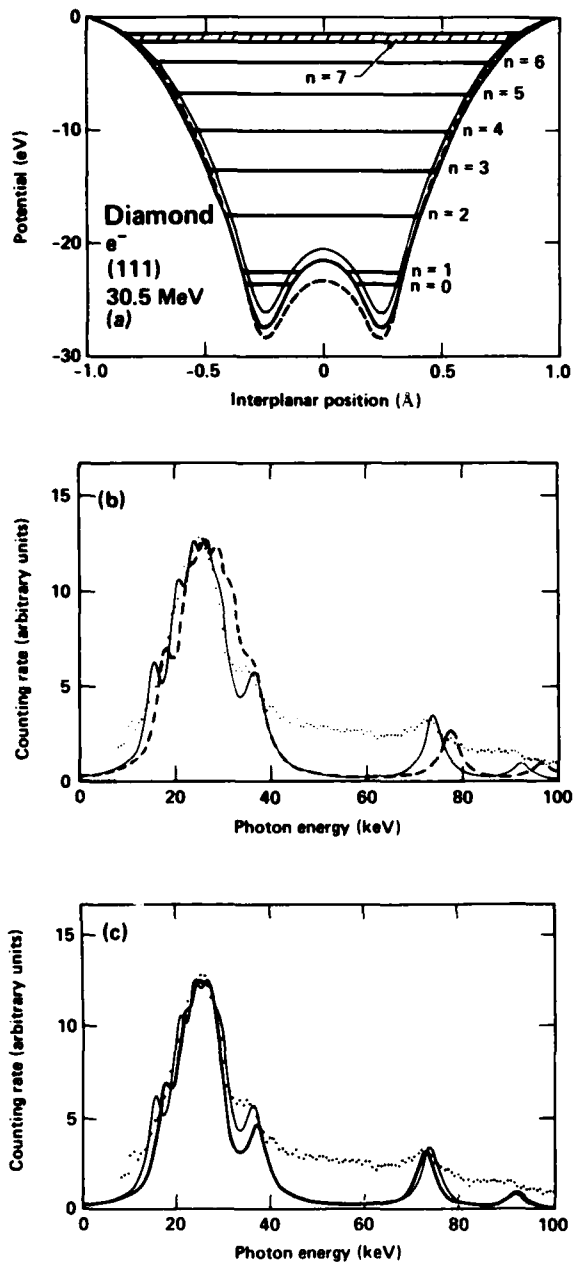
Fig. 2. (a) (111) potentials for diamond: the "standard" many-beam potential (dashed curve); a potential based upon X-ray diffraction data (light solid curve); and an empirical potential based upon the best fit to the 30.5-MeV data (heavy solid curve), together with the corresponding eigenvalues. (b) The (111) spectrum for 30.5-MeV electrons, together with the calculated spectra obtained from the standard (dashed curve) and X-ray diffraction (light solid curve) potentials. (c) The same spectrum, together with the spectra calculated from the X-ray diffraction (light solid curve) and empirical (heavy solid curve) potentials.
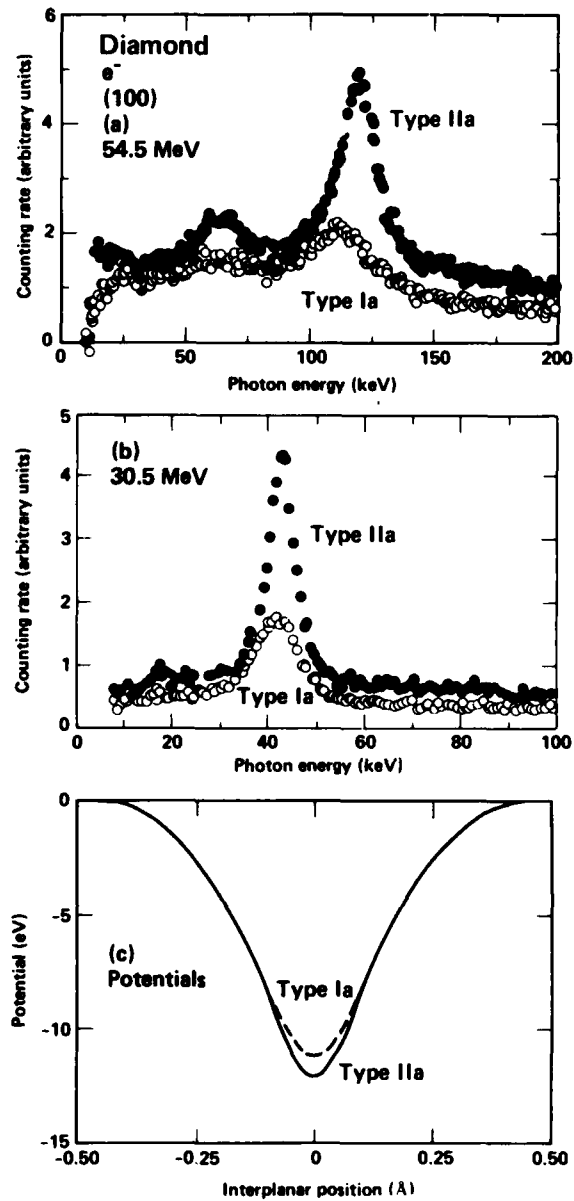

Fig. 3. (100) channeling-radiation spectra from both Type-Ia (with platelets; open data points) and Type-IIa (without platelets; closed data points) diamonds for (a) 54.5-MeV and (b) 30.5-MeV incident electrons. Note in particular the energy shift for the $1 \rightarrow 0$ transition. (c) (100) potentials for diamond: the one which uses the accepted value of 0.040 Å for the thermal-vibration amplitude, as is appropriate for the Type-IIa diamond (solid curve) and the one which uses the value of 0.055 Å, which arises from the best fit to the data for the Type-Ia diamond (dashed curve).

neling radiation dramatically [19–22]. In particular, they cause an energy shift in the (100) spectral lines, as shown in fig. 3. We have shown recently that these

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lineshifts can be accounted for by equating the lattice distortion caused by the platelets with a large *average* thermal-vibration amplitude perpendicular to the (100) planes and hence to the platelets. The (100) potential so altered also is shown in fig. 3; the numerical results are given in ref. [22]. These results also serve to show that channeling radiation can be used as a sensitive diagnostic probe of impurities and defects in crystals.

4. Debye temperature

Although some results on the dependence of channeling-radiation transition energies upon temperature have been published previously [32–34], only recently have we been able to study the shifts in transition energies and linewidths for many planar transitions down to near-liquid-nitrogen temperature. Some of these results, namely those for the (100) and (110) spectra for 54.5-MeV electrons in silicon (taken from ref. [35]), are shown in fig. 4. The temperature dependence of the
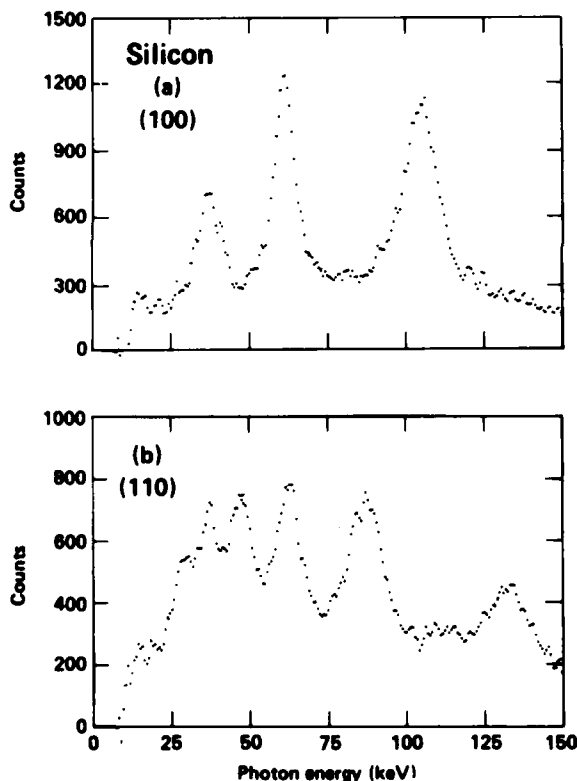
Fig. 4. Superposed channeling-radiation spectra for 54.5-MeV electrons incident along the (a) (100) and (b) (110) planes of silicon for two different temperatures: (a) −190°C (heavy data points) and +5°C (light data points); (b) −180°C (heavy data points) and +7°C (light data points). Note the large energy shifts of the 1 → 0 transitions.
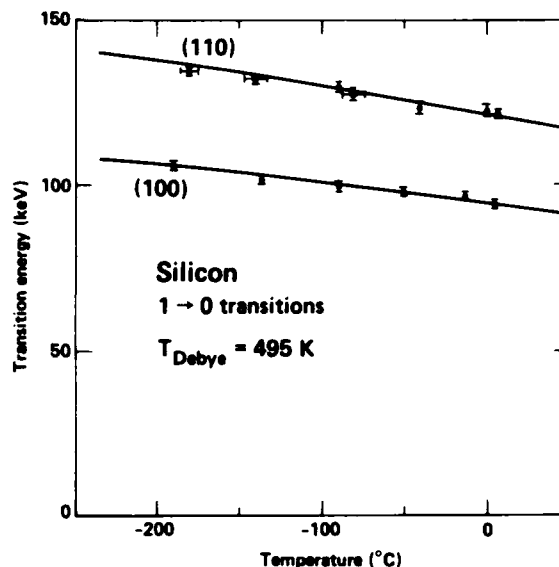
Fig. 5. Temperature dependence of the channeling-radiation transition energies for the 1 → 0 transitions of 54.5-MeV electrons channeled along the (100) and (110) planes in silicon. The fits to these data (solid curves) yield a consistent value of 495 ± 10 K for the Debye temperature of silicon. Curves corresponding to a Debye temperature of 543 K would exceed the curves shown here by approximately 10 keV.

transition energies for the lowest-lying energy levels (the 1 → 0 transitions), shown in fig. 5, is sensitively dependent upon the assumed Debye temperature. These data consistently yield a value for the Debye temperature of silicon of 495 ± 10 K, in sharp disagreement with the value of 543 ± 8 K obtained from X-ray diffraction studies [36]. Various theoretical models yield results which vary from 500 to 530 K [37]. Our results thus serve to show that channeling-radiation data can be used to determine Debye temperatures.

5. LiH and LiD

Our recent results for LiH and LiD [24] show two interesting effects for these lowest-Z crystals. One is the largest disagreement to date between measured and calculated transition energies, as shown, for example, in fig. 6 for the case of 54.5-MeV positrons and electrons incident along the (100) and (110) planes of LiH. The other can be seen in fig. 7, where (110) channeling-radiation spectra from LiH and LiD (both obtained at room temperature) are superposed. It is immediately evident that the value of the thermal-vibration amplitude for LiD is smaller than that for LiH, as one would expect from the fact that deuterons are heavier than protons, and so cause LiD to appear as a low-temperature ver-
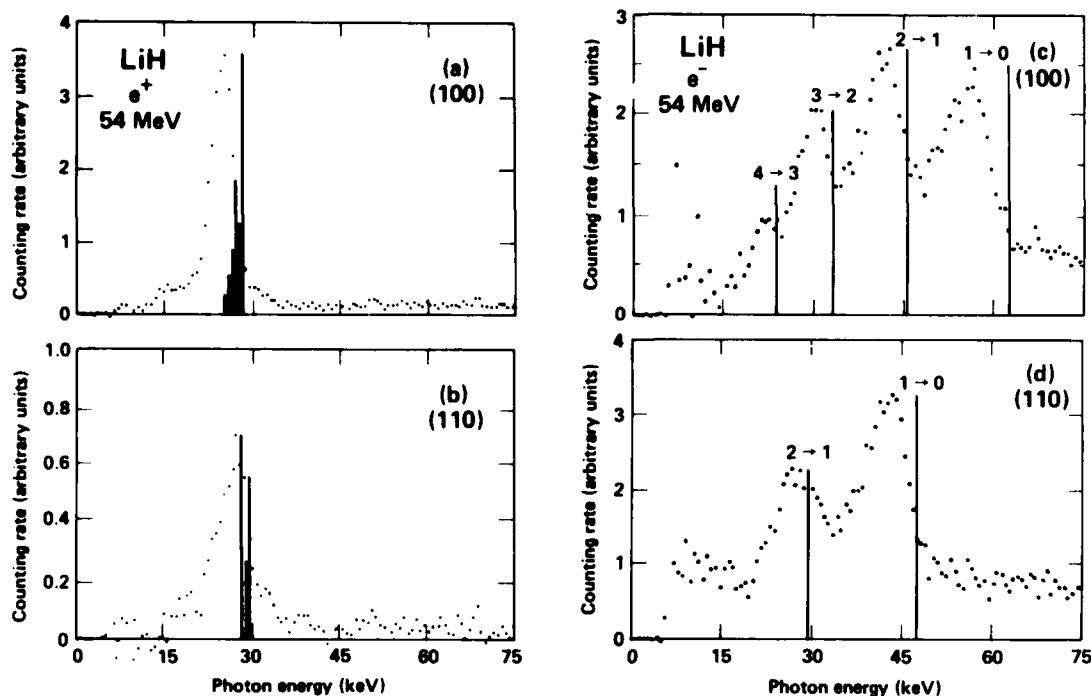
Fig. 6. Channeling-radiation spectra for LiH, both for 54.5-MeV positrons incident along the (a) (100) and (b) (110) planes and for 54.5-MeV electrons incident along the (c) (100) and (d) (110) planes, together with the calculated transition energies and strengths (vertical lines) obtained from the standard many-beam theoretical treatment. Note the very large discrepancies between experiment and theory.
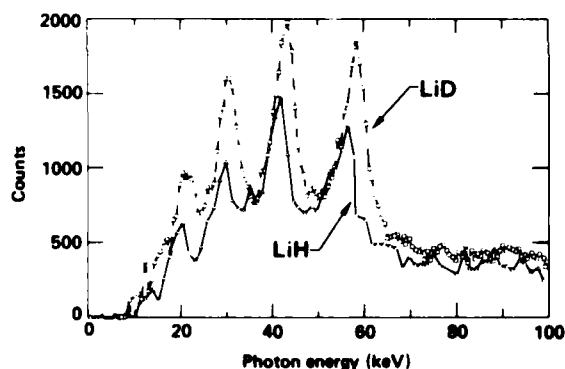

Fig. 7. Superposed-radiation spectra for 54.5-MeV electrons incident along the (100) planes of LiH (triangles) and LiD (squares). Note that the LiD spectrum resembles a spectrum that one might expect to obtain from a cooled LiH crystal.

sion of LiH. This result, however, contradicts the previously accepted value for LiD which (incredibly) is larger than that for LiH [38]. This is the first identification of an isotopic effect in a crystal by channeling radiation.

6. Damaged LiF

Perhaps the most important potential application of channeling radiation is as an intense, easily tunable source of monochromatic, forward-directed, polarized photons. In order to test whether one could continue to produce channeling radiation from a crystal that had undergone extensive radiation (by the electron beam that produces the channeling radiation), we irradiated a number of identical LiF crystals with various large beam fluxes of 54.5-MeV electrons. Some of the results of this first exploration of this effect [39] are shown in fig. 8. These (100) channeling-radiation spectra for 54.5-MeV positrons show a remarkable survivability of enough of the crystal structure of (easily damaged) LiF to continue to produce channeling radiation even after very large radiation doses.

We also learn something about crystal damage mechanisms from such studies. In fact, from the linewidths of the irradiated LiF crystals, the density of defects can be estimated, and from this density the cross section for atomic knockout is determined to be ~ 700 b. In comparison, the cross section for silicon for the same experimental parameters has been calculated to be ~ 200 b [40]. Therefore, the damage rate in LiF is approximately 3.5 times the rate in silicon. In addition, the electron-

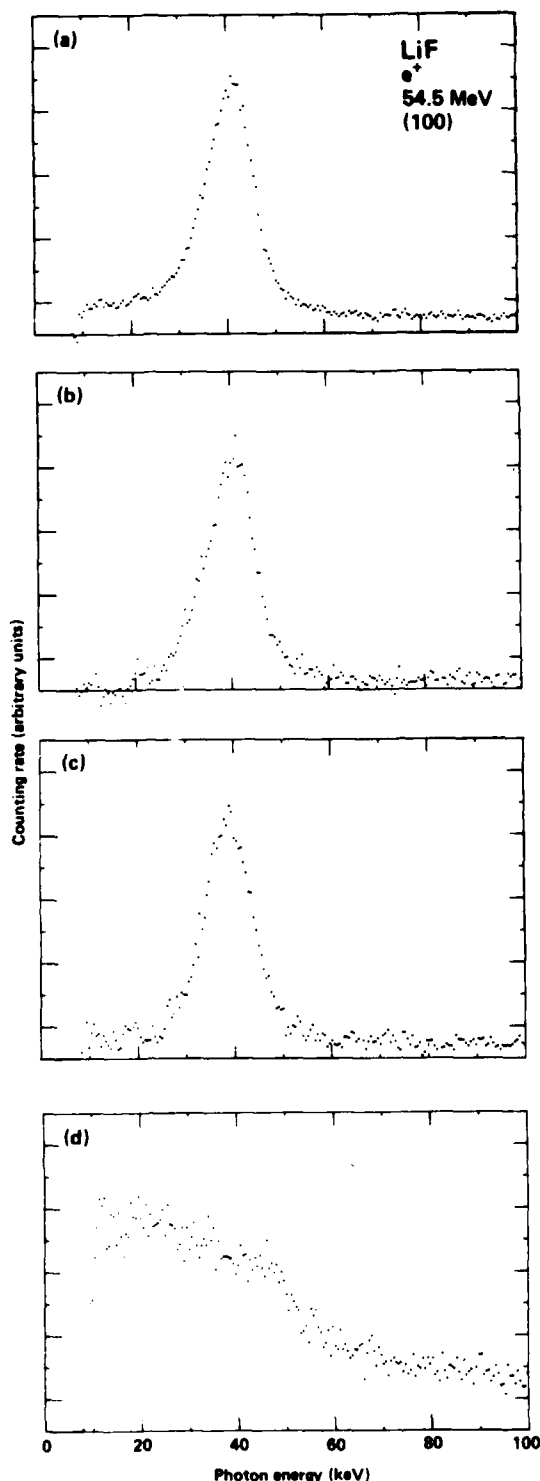channeling data show that the Li atoms are more easily displaced from their lattice sites than the F atoms, as expected.

7. Conclusion and perspective

Channeling-radiation studies have come of age. Not only are the properties of channeling radiation themselves of great interest, but channeling-radiation measurements have shown themselves to be sensitive diagnostic tools for the determination of the properties both of perfect and of damaged, defective, or impure crystals. Finally we are a step closer to the use of channeling radiation as a powerful and versatile photon source.

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Fig. 8. Channeling-radiation spectra from 54.5-MeV positrons incident along the (100) planes of LiF, for four initially identical crystals: (a) an undamaged crystal (no significant radiation dose); (b) a lightly damaged crystal [irradiated enough to

displace (in theory) 1% of the ionic cores (the lattice nuclei)]; (c) a moderately damaged crystal [irradiated with 10 times the dose of (b)]; and (d) a heavily damaged crystal [irradiated with 100 times the dose of (b)]. Note that the character of the channeling-radiation spectrum is seriously degraded only for this heaviest dose.

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